

# INFLATION AND INVERSE SYMMETRY BREAKING

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An inflation model with inverse symmetry breaking of two scalar fields is proposed. Constraints on the parameters for a successful inflation are obtained. In general the inequality  $\lambda_1 \ll g < \lambda_2$  should be satisfied, where  $\lambda_{1,2}$  and  $g$  are the coupling constants for self interaction and mutual interaction of two scalar fields respectively. An example with  $SU(5)$  GUTs phase transition and numerical study are presented. This model introduce a new mechanism for the onset of inflation.

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# I. INTRODUCTION

Various inflation models[1] have been proposed to solve the horizon and the flatness problems of the standard Big Bang cosmology. However, in relation to particle physics each model has its own problems to be solved. Therefore, reconciling the inflation models with particle physics is an important subject of the modern cosmology.

Since the upper bound on the inflation energy scale is about the GUTs(Grand Unified Theories) scale[2], it is natural to search for the inflation during the GUTs phase transition. However, the original inflation model has graceful-exit problem[1] and ‘new’ inflation model with the GUTs nonsinglet fields leads to too strong density fluctuation[3]. As a solution to this problem the model with the GUTs singlet inflaton coupled with SU(5) Higgs was suggested[4].

Generally, the smallness of the coupling constants required for the small density perturbation prevents inflaton fields from obtaining thermal-equilibrium, while chaotic inflation model[5] uses this non-equilibrium states to give the initial conditions for the inflaton fields.

Though many aspects of the phase transition theory have already been used for the various inflation models, field theory has still other mechanisms of the phase transition to be studied in the context of inflation.

In this paper, an inflation model with ‘inverse symmetry breaking’ is investigated. Inverse symmetry breaking[6] is a phenomenon that the symmetry

broken at a higher temperature is restored at a lower temperature, contrary to the ordinary phase transitions. The phenomenon has been applied to solving the monopole problem by allowing the temporary breaking of the  $U(1)$  gauge symmetry[7]. Similar phenomenon called anti-restoration appears in some global SUSY theories[8].

Our model is a kind of two fields inflation models[9] where generally an additional scalar field besides inflaton is introduced to complete the inflation and/or give an appropriate density perturbations. For example, in the ‘hybrid’ or ‘false vacuum’ inflation model[10] the additional scalar field gives the inflaton extra masses which make the inflaton roll down and end the inflation.

The inflaton potential in our model is similar to that in the hybrid model, but the detailed features of the phase transition are very different. In our model the phase transition of a scalar field (say  $\phi_2$ , for example GUTs Higgs) is responsible for the beginning of the inflation driven by a gauge singlet inflaton(say  $\phi_1$ ) rather than the ending of the inflation. Moreover, the additional field( $\phi_2$ ) is in the true vacuum rather than the false vacuum during the inflation.

In sec. II, we review inverse symmetry breaking and derive the conditions for the phenomenon. In sec. III, the constraints for the successful inflation is derived. In sec. IV, an application with  $SU(5)$  GUTs model and numerical study are presented. Sec. V contains discussions.

## II. INVERSE SYMMETRY BREAKING

In this section we review inverse symmetry breaking and conditions required for it. Consider a following potential which is a simple example of inverse symmetry breaking. Such a potential can appear in the approximation of the 1-loop finite temperature effective potential of the two interacting massive scalar fields.

$$\begin{aligned} V(\phi_1, \phi_2, T) = & (D_1 T^2 - \mu_1^2) \phi_1^2 + \lambda_1 \phi_1^4 \\ & + (D_2 T^2 - \mu_2^2) \phi_2^2 + \lambda_2 \phi_2^4 + g \phi_1^2 \phi_2^2 + C, \end{aligned} \quad (1)$$

where  $-\mu_i^2 \phi_i^2 (i = 1, 2)$  is the bare mass term of  $\phi_i$ , and  $D_i$  is the coefficient of thermal mass correction term[11]. Here the constant  $C$  is introduced to make the cosmological constants zero.

The mutual interaction term:

$$V_{int} = g \phi_1^2 \phi_2^2. \quad (2)$$

is essential for inverse symmetry breaking. We will consider the case where this term exists in the tree level potential. This term may also arise via fermion exchange box diagrams, even if it is absent in the tree level potential [12].

When the fields have v.e.v.(vacuum expectation value), they acquire additional masses through  $V_{int}$ . Their effective masses squared at a temperature  $T$  without  $D_i T^2$  terms are

$$m_{1ef}^2(T) \equiv 2(-\mu_1^2 + g \langle \phi_2(T) \rangle^2), \quad (3)$$

$$m_{2eff}^2(T) \equiv 2(-\mu_2^2 + g\langle\phi_1(T)\rangle^2), \quad (4)$$

where  $\langle\phi_i(T)\rangle$  is the v.e.v. of  $\phi_i$  at  $T$ .

Then the phase transition temperature  $T_{ci}$  at which the coefficient of  $\phi_i^2$  vanishes can be defined, *i.e.*,

$$T_{ci}^2 \equiv -\frac{m_{ieff}^2(T_{ci})}{2D_i}. \quad (5)$$

From now on we will consider the case

$$T_{c1} > T_{c2}, \quad (6)$$

which means that  $\langle\phi_1(T)\rangle$  becomes nonzero at  $T_{c1}$ , and after the expansion of the universe  $\langle\phi_2(T)\rangle$  becomes nonzero at the lower temperature  $T_{c2}$  in turn. If  $\langle\phi_2(T)\rangle$  is sufficiently large at  $T_{c2}$ , the symmetry of  $\phi_1$  broken at  $T_{c1}$  can be restored due to the additional mass term from  $V_{int}$  (see eq.(4) and Fig.1.). This is so-called ‘Inverse symmetry breaking’[6].

If at this temperature( $T_{c2}$ )  $\phi_1$  rolls down slowly from  $\langle\phi_1(T_{c2})\rangle$  to zero and its energy dominates others, we can expect a chaotic type slow-rollover inflation and regard  $\phi_1$  as an inflaton field. Note that here we use the terminology ‘chaotic’ to mean a kind of inflation potential and not chaotic initial condition[13].

$\langle\phi_i(T)\rangle$  can be found from the relation  $dV(\phi_1, \phi_2, T)/d\phi_i = 0$ . From eq.(1) one can obtain

$$\langle\phi_1(T)\rangle = \sqrt{\frac{\mu_1^2 - g\langle\phi_2(T)\rangle^2 - D_1 T^2}{2\lambda_1}} \simeq \sqrt{\frac{\mu_1^2}{2\lambda_1}} \equiv \sigma_1, \quad (7)$$

when  $T_{c2} < T < T_{c1}$ .

The above approximation is justified by the facts that  $\langle\phi_2(T)\rangle = 0$  in this temperature range, and  $D_1T^2$  term decreases rapidly after the phase transition at  $T_{c1}$  ( see again Fig.1. ).

And similarly when  $T < T_{c2}$ ,

$$\langle\phi_2(T)\rangle \simeq \sqrt{\frac{\mu_2^2}{2\lambda_2}} \equiv \sigma_2. \quad (8)$$

From now on, to simplify the calculation, we will use  $\sigma_i$  as an approximation of  $\langle\phi_i(T)\rangle$  in the temperature region described above. It is a good enough approximation for the order of magnitude estimates.

Note that  $\sigma_1$  and  $\sigma_2$  minimize  $V(\phi_1, 0, 0)$  and  $V(0, \phi_2, 0)$  respectively.

### III. CONSTRAINTS FOR THE INFLATION

In this section the conditions for a successful inflation will be obtained. There are many constraints for the successful inflation models. The most significant one comes from the density perturbation:

$$[\frac{\Delta T}{T}]_Q^2 = \frac{32\pi V_{inf}^3}{45V_{inf}'^2 M_P^6}, \quad (9)$$

where  $V_{inf}'$  is  $\frac{dV_{inf}}{d\phi_1}$  at the horizon crossing of the observed scale. We consider the quadratic term dominated inflaton potential  $V_{inf} \equiv m_1^2\phi_1^2/2$  which is the  $\phi_1$  dependent part of the approximation of  $V(\phi_1, \phi_2, T \leq T_{c2})$ . So  $m_1^2/2 \simeq -\mu_1^2 + g\sigma_2^2$ .

COBE[14] observation,  $[\frac{\Delta T}{T}]_Q \simeq 6 \times 10^{-6}$ , demands  $m_1 \simeq 10^{13} GeV$  for our model.

Sufficient expansion condition requires[15]

$$\sigma_1 = \sqrt{\frac{N}{2\pi}} M_P \gtrsim 3M_P \quad (10)$$

for  $e^N$  expansion and  $N \gtrsim 60$ .

Note that for the quadratic term dominated inflaton potential slow-rolling condition  $m_1 \ll H$  is automatically satisfied for  $\sigma_1 \gtrsim M_P$ . The above two constraints are common to many mass term dominated chaotic type inflation models.

Now we will investigate conditions specific for our model.

First, the condition for inverse symmetry breaking(eq.(6)) is equal to

$$\frac{\mu_1^2}{D_1} > \frac{\mu_2^2 - g\sigma_1^2}{D_2}. \quad (11)$$

Second, the phase transition at  $T_{c2}$  must be energetically favorable to take place. It means that the free energy released by symmetry breaking by  $\phi_2$  must be larger than the free energy absorbed by symmetry restoration by  $\phi_1$ . This implies

$$V(\langle\phi_1(T)\rangle, 0, T \geq T_{c2}) - V(0, \langle\phi_2(T)\rangle, T \leq T_{c2}) > 0, \quad (12)$$

or approximately  $V(\sigma_1, 0, 0) - V(0, \sigma_2, 0) > 0$ , which is equivalent to

$$\mu_1^2 \sigma_1^2 < \mu_2^2 \sigma_2^2. \quad (13)$$

Third, restoring the symmetry of  $\phi_1$  implies  $m_{1eff}^2(0) > 0$ , or

$$\mu_1^2 < g\sigma_2^2. \quad (14)$$



Similarly, the broken symmetry of  $\phi_2$  implies  $m_{2eff}^2(0) < 0$ ,

$$\mu_2^2 > g\sigma_1^2. \quad (15)$$

From eq.(11) and eq.(13) we obtain

$$D_1 < \frac{\mu_1^2}{\mu_2^2 - g\sigma_1^2} D_2 \simeq \frac{\mu_1^2}{\mu_2^2} D_2 < \left(\frac{\sigma_2}{\sigma_1}\right)^2 D_2, \quad (16)$$

where we have used eq.(15) in the approximation.

And finally, we want the potential  $V_{inf}$  to be dominated by  $\phi_1^2$  term rather than by  $\phi_1^4$  term. So

$$\mu_1^2 < \frac{2}{3}g\sigma_2^2. \quad (17)$$

Using eq.(7) and eq.(8), one can rewrite the constraints(eq.(11) and eq.(13)) with  $\lambda_i$  instead of  $\mu_i$ .

$$\lambda_1\left(\frac{\sigma_1}{\sigma_2}\right)^4 < \lambda_2 < \lambda_1\left(\frac{\sigma_1}{\sigma_2}\right)^2 \frac{D_2}{D_1} + \frac{g}{2}\left(\frac{\sigma_1}{\sigma_2}\right)^2. \quad (18)$$

Let us further consider miscellaneous constraints. One loop correction to  $\lambda_i$  should not be larger than itself, i.e.,  $\lambda_i \gtrsim 0.1g^2$ .

Whether  $\phi_2$  drives an inflation or not at  $T_{c2}$ ,  $\phi_2$  oscillates around the potential minima( $\sigma_2$ ) with period  $\sim 1/m_2$  after the phase transition (see fig.1), and its energy density  $\rho_{\phi_2}$  decreases as  $R^{-3}(t)$  like classical nonrelativistic matter field[16]. Here  $m_2^2/2 \equiv -\mu_2^2 + g\sigma_1^2$  is an approximation of  $m_{2eff}^2(T)$  at  $T_{c2} \leq T < T_{c1}$ .

Since  $R \propto t^{2/3}$  in the matter dominated era,  $\rho_{\phi_2}$  is proportional to  $t^{-2}$  during the oscillation. (Even if  $\rho_{\phi_2}$  rapidly changes to radiation energy so that the

universe is in radiation-dominated era, the energy density is proportional to  $t^{-2}$  and the above arguments still hold.)

We need to know the time ( $\Delta t_{osc}$ ) when  $\rho_{\phi_2}$  decreases to  $\rho_{\phi_1}$  and the inflation by  $\phi_1$  begins. From the fact that  $\rho_{\phi_2}(t) \simeq \rho_{\phi_2}(t_2)H(t_2)^{-2}t^{-2}$  this time scale is given by

$$\Delta t_{osc} \simeq \frac{1}{H(t_2)} \left[ \frac{\rho_{\phi_2}(t_2)}{\rho_{\phi_1}} \right]^{\frac{1}{2}} \sim \frac{M}{m_1 \sigma_1}, \quad (19)$$

where  $M \equiv M_P/8\pi$  is the reduced Planck mass,  $t_2$  is the time when the oscillation of  $\phi_2$  starts and  $H(t_2) \sim m_2 \sigma_2 / M \sim \rho_{\phi_2}^{\frac{1}{2}} / M$ . We have also used the fact that  $\rho_{\phi_i} \sim m_i^2 \sigma_i^2$  before  $\phi_i$  start to oscillate.

During  $\Delta t_{osc}$ ,  $\phi_1$  should not fall down too much. Since the equation for  $\phi_1$  is

$$3H\dot{\phi}_1 = -m_1^2 \phi_1, \quad (20)$$

whose solution is  $\phi_1 = \sigma_1 - m_1 M_P t / 2\sqrt{3}$ [15], the rolling time scale is  $\Delta t_{rol} \sim 1/m_1$ . (the dots denote time derivatives.) Therefore one can know that if  $\sigma_1 \gg M$ ,  $\Delta t_{osc} \ll \Delta t_{rol}$  and  $\phi_1$  does not decrease too much during  $\phi_2$  oscillation, and one could expect the inflation by  $\phi_1$ .

## IV. AN EXAMPLE WITH $SU(5)$ GUTs AND NUMERICAL STUDY

Let us apply our model to  $SU(5)$  GUTs. Consider the case where  $\phi_2$  is a  $SU(5)$  Higgs field[3]. Then the phase transition temperature  $T_{c2} \simeq 10^{15} GeV \simeq$

$\sqrt{(\mu_2^2 - g\sigma_1^2)/D_2} \simeq \sqrt{\mu_2^2 - g\sigma_1^2}$ , because  $D_2 = \frac{75}{8}g_{SU(5)}^2 \simeq 3$  with the unified gauge coupling  $g_{SU(5)}$ .

We also know that  $\sigma_2 \simeq M_X/g_{SU(5)} \simeq 10^{15}GeV$ .

From eq.(10) and eq.(16) it is easy to find that

$$D_1 < \left(\frac{\sigma_2}{\sigma_1}\right)^2 D_2 \lesssim 10^{-8}. \quad (21)$$

From the density perturbation constraint  $m_1^2/2 \simeq (10^{13}GeV)^2 \simeq -\mu_1^2 + g\sigma_2^2 \leq g\sigma_2^2$  we get  $g \gtrsim 10^{-4}$ . However  $D_1 \simeq 0.1g < 10^{-8}$ , so  $g < 10^{-7}$ . Hence  $g$  can not satisfy the both conditions. This problem is easily solved by considering the GUTs models whose energy scale is larger ( $T_{c2} \simeq 10^{16}GeV$ ). In this case, using the same procedure we obtain  $g \gtrsim 10^{-6}$  and  $D_1 \lesssim 10^{-6}$ , so all the condition is satisfied within our approximation.

From eq.(14) and eq.(7) we obtain

$$\lambda_1 < \frac{g}{2} \left(\frac{\sigma_2}{\sigma_1}\right)^2 \lesssim 10^{-12}, \quad (22)$$

so  $\lambda_1 \ll g$ .

Such a small coupling constant is typical to many slow-rollover inflation models, and gives rise to a thermal non-equilibrium problem. Like many other slow-rollover inflation models except for the chaotic inflation model, it is very hard to establish initial thermal equilibrium required for our model.

For the following, we will assume that somehow this equilibrium is established and  $\phi_i$  has the appropriate initial values. ( The parametric resonance

mechanism[17] may help good reheating, but it is still unclear that produced light particles can obtain the thermal equilibrium before  $T_{c2}$ .)

If we want any inflation at  $T_{c2}$ , the vacuum energy of  $\phi_1$  or  $\phi_2$  must be larger than the radiation energy. In this case, from eq.(13) the energy of  $\phi_2$  is larger than that of  $\phi_1$ , so it is possible that there is a new inflation by ' $\phi_2$ ' before that by  $\phi_1$ . So our model could be a kind of 'double inflation'[18].

Whether the first inflation(by  $\phi_2$ ) can exist depends on the rolling speed of  $\phi_2$  at this phase transition. Since the number of e-foldings of expansion in the new inflation is given by  $N \simeq (H/m_2)^2$ , the first slow-rollover inflation is available only for  $m_2 \ll H$ .

However, from the fact that  $m_2^2/2 = -\mu_2^2 + g\sigma_1^2$ , one can know that  $m_2 \gg H_2 \simeq 10^{13}GeV$  without fine tuning and there is no slow-rollover inflation driven by  $\phi_2$  preceding  $\phi_1$  inflation with GUTs.

Now we will discuss the numerical study of our model. The process of our inflation model seems to be rather complicated. To confirm the scenario we perform numerical study of following equations for the evolution of the fields:

$$\begin{aligned} H &= [\frac{1}{3M^2}(\frac{\dot{\phi}_1^2}{2} + \frac{\dot{\phi}_2^2}{2} + V)]^{\frac{1}{2}}, \\ \ddot{\phi}_i + 3H\dot{\phi}_i + \frac{\partial V}{\partial \phi_i} &= 0, \end{aligned} \tag{23}$$

where  $V$  is  $V(\phi_1, \phi_2, 0)$  in eq.(1). We have ignored thermal contributions which may become small relatively when there is inflation or oscillation of  $\phi_1, \phi_2$ .

Fig.2 shows the results with  $m_1 = 10^{13}GeV$ ,  $m_2 = 5 \times 10^{16}GeV$ ,  $\sigma_1 = 5M$ ,  $\sigma_2 =$

$5 \times 10^{-2}M$  and  $g = 10^{-7}$ .

After the long oscillation of  $\phi_2$  for  $\tau \gtrsim 11$  (in realistic case, this oscillation disappears rapidly by producing particles.),  $\rho_{\phi_2}$  decreases and  $\phi_1$  rolls down and begin the inflation. The sign of the inflation by  $\phi_1$  can be identified by the flat region of  $H$  graph(  $\tau \gtrsim 16$ ). After the inflation ends,  $\phi_1$  starts to oscillate when  $\tau \simeq 19$ .

Now let us consider the case where no initial thermal equilibrium state is established. It is well known that at the Planck scale the typical initial value of  $\phi_1$  could be about  $\lambda_1^{-1/4} M_P \gg M_P$ . Hence, generally there could be an chaotic inflation by  $\phi_1$  before the inflation by  $\phi_1$  and/or by  $\phi_2$  at the lower temperature.

Whether there has been a chaotic inflation or not,  $\phi_1$  field rolls down to  $\sigma_1$  and start to oscillate when  $\phi_1 - \sigma_1$  becomes about  $M_P$ . Since  $m_2 \gg m_1$ , during the chaotic inflation  $\phi_2$  rolls down to  $\sigma_2$  rapidly, then the effective mass of  $\phi_1$  becomes positive and  $\phi_1$  may roll down to zero again. In this case our scenario is hardly distinguishable from the ordinary chaotic inflation by  $\phi_1$ . So it seems to be essential to assume the initial thermal equilibrium, if we consider our model with GUTs.

## V. DISCUSSIONS

The most special feature of our model is that we can choose the initial value of the inflaton field( $\sigma_1$ ) by varying the parameters.

From eq.(18) and eq.(22) we know that the relation  $\lambda_1 \ll g < \lambda_2$  should be satisfied for the successful inflation.

For some parameter ranges our model could be a two-field double inflation whose properties depend on the rolling speed of  $\phi_2$ .

Our model with the GUTs phase transition requires the GUTs energy scale to be  $O(10^{16} GeV)$ , while assumption of thermal equilibrium is needed like many other slow-rollover inflation models.

The numerical study indicates that in spite of complexity of our model inflation could occur with parameters constrained by many conditions.

This model may also be used to give the appropriate density perturbation to match COBE normalization with galaxy-galaxy correlation function[19]. Note that for this purpose  $\sigma_1$ ( eq.(10)) should be lowered so that we can observe the effect of the inflation by  $\phi_2$ .

Many constraints on the masses and couplings of the fields for the successful inflation and inverse symmetry breaking are studied. However, some of the requirements can be abandoned. For example,  $\phi_1$  needs not have zero v.e.v. after inflation and may have some finite v.e.v. In this case,  $\phi_1$  could be a scalar field responsible for the broken symmetry in some particle physics theories.

It is also possible that inflaton potential is dominated by quartic term not by quadratic term.

Furthermore, for more general case the potential  $V(\phi_1, \phi_2, T)$  may have small

barrier term such as  $T\phi_i^3$ . In this case, it is possible that there is a first order inflation by  $\phi_2$  which is interesting, because it could be another mechanism for the recently proposed open inflation models[20].

In a word, there still remain various scenarios to be studied in different parameter spaces in this model where the new way of onset of inflation is introduced.

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## Figure Caption

Fig.1. Schematic diagram for inverse symmetry breaking.

$\langle\phi_1(T)\rangle$ (thick line) and  $\langle\phi_2(T)\rangle$ (dashed line) versus temperature  $T$ .

Fig.2. The results of numerical study showing the evolution of  $\phi_1, \phi_2$  and  $H$  versus time in log scale  $\tau = \ln(m_2 t)$ .  $\phi_1$  is in units of  $M$ ,  $\phi_2$  in units of  $10^{-2}M$  and  $H$  in units of  $10^{-2}m_2$ .



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